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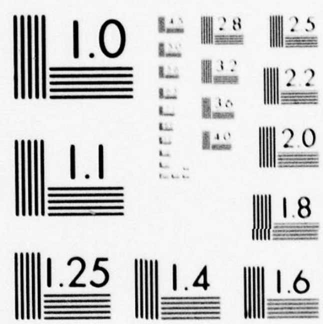

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Rapid Sampling of Temperature and Temperature Gradient using XBT's

Bill P. Johnson

R. Edward Lange

Supported by the Office of Naval Research

Contract N00014-75-C-0152

15 March 1979 SIO Reference Series #79-4

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During the summer of 1977, as part of the near-surface component of the POLYMODE Local Dynamics Experiment, a set of observations of temperature variability was undertaken. One subset of these observations was undertaken by the authors.

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Rapid Sampling of Temperature and Temperature Gradient using XBT's

(10)

Bill P. Johnson

R. Edward Lange

Supported by the Office of Naval Research

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INTRODUCTION

During the summer of 1977, as part of the near-surface component of the POLYMODE Local Dynamics Experiment, a set of observations of temperature variability was undertaken. One subset of these observations was undertaken by the authors.

There were two goals of the author's field experiment--first to examine the extent of variability in isotherm displacements, on a small (approximately 2 km grid) scale, to explore further and in more detail the preliminary observations of Ants Leetma (POLYMODE News #32) and secondly to apply the developed technology of band-passed sampling of temperature structures to an expendable bathythermograph (XBT).

The technical details of the second goal only, are outlined in this technical report. The results of the first goal will be the subject of a forthcoming paper to be submitted to Deep Sea Research.

For several years now (since 1975), a modified version of the 750 meter XBT probe (T-7) has been available. This modified probe has most of the zinc nose weight removed to slow descent rate from 6.5 meters per second to 1.7 meters per second. It is manufactured by the Sippican Corporation of Marion, Massachusetts, and is termed the "fine structure XBT", and designated a T-11. Because of the constraints placed upon cost

and reliability of thermistors used in XBT's, Sippican chose to slow descent rate to record fine-structure variability, rather than modify existing thermistor manufacturing techniques.

Since the authors have had extensive experience in the measurement and interpretation of thermal fine structure in the ocean through the use of free-fall vehicles, it seemed appropriate to apply that experience to a commercially available profiler of high reliability and low cost. The motivation for this was two-fold. First it appeared that little or no use of the T-11 had been made by the oceanographic community to date, and its potentials not fully explored. Second, there is a great need to have the capability to rapidly conduct areal surveys of fine scale temperature variability (such as found near transient frontal activity, rapidly moving mesoscale eddy features, internal wave induced mixing events, laterally moving intrusive and double diffusive phenomena, to name a few).

The engineering rationale for sampling a thermistor device of time constant about 100 milliseconds, at rates up to and exceeding 50 samples per second, lies in the form of the differential heat conduction equation:

$$\frac{\partial T}{\partial t} = K \nabla^2 T + \text{source and sink terms} \qquad (1)$$

where T is temperature

t is time

k is the bulk thermodynamic diffusivity

and ∇ is the Laplace operator

This equation is linear in temperature, and to the best of our knowledge, the transfer of heat to and from a thermistor moving in a fluid of varying temperature is also a linear process (given steady flow and steady boundary layer configuration).

It then follows that the signal generated by a varying resistance thermistor is linearly related to the temperature structures the thermistor encounters. Thus, in spectral terms, the frequency components of the temperature fluctuations that occur at a faster rate than the response time of the thermistor will be attenuated by a given, constant attenuation factor, dependent only upon the frequency, and the thermistor-to-thermistor variability--not on the level of the temperature fluctuations measured. Given uniform response characteristics of thermistors, it is thus possible to spectrally correct for thermistor response at frequencies well above the time constant of the thermistor, limited only by the noise arising from undocumented and varying sources, and the time-space constancy of the bulk diffusivity of heat.

This report is based on a preliminary evaluation of the potential of the T-11 in fulfilling the above-outlined considerations. The T-11 was found to be quieter overall, and more responsive and repeatable in its characteristics than the authors anticipated. As a result, the T-11 "outperformed" the

capabilities of the data acquisition system designed for the experiment.

Work is continuing in this regard, and a final report (supplementary to the present one) will be forthcoming.

System Configuration

The signal conditioning and recording system consists of the standard XBT and launcher with associated cables connected to an in-house constructed bridge, power supply, amplifiers and filters. This equipment was connected to a data acquisition module on a Tektronix 4051 micro-computer graphic display unit. The 4051 is equipped with a 30 character per second line printer and a hard copy device. The bridge circuits and filters are duplicated so that 2 XBTs may be recorded simultaneously. Each bridge circuit has associated with it a DC circuit which yields temperature and a high passed (AC) circuit which produces a measure of the temperature gradient. The pass bands of the temperature gradients have switch selectable filter sections as do the DC temperature sections. During this experiment the filters had switch settings for 8, 15 and 40 Hertz (half-power) points on the high end of the frequency pass bands. The low end of the pass band was set at 0.1 Hertz. The 4051 and data acquisition unit can sample either one channel of temperature, 2 channels of temperature, one channel of temperature and one channel of temperature gradient or 2 channels of temperature and

temperature gradient. The data acquisition system is shown in Figure 1.

Error Budgets

The signal acquiring circuits shown in Figure 2 consist of a pair of current sources, whose output can be precisely set and which will track each other over a wide temperature range. This circuit thus presents an output when measured differentially which is an analog of the unbalanced legs of a symmetrical bridge. The output varies linearly with resistance change of the XBT probe. The allowable common mode resistance, that is, the resistance between the sea water contact of the XBT probe in the water and the connection to the ship's hull is set by the voltage available to the precision current sources. In our circuit it is approximately 40 k (ohm). The common mode error is set by the instrumentation amplifier and is specified at >100 db. This produces a maximum error assuming a 40 K change in common mode resistance (not a typical occurrence) of

$$\frac{40000}{10^5\ (100\text{db})} = 0.4\Omega \text{ common mode error} \tag{2}$$

Given a nominal 7000 ohm thermistor with 4.52%/°C change in resistance due to temperature this represents

$$7000\ \Omega \times 0.0042 = 31.6\ \Omega/^{o}\text{C} \tag{3}$$

or

$$\frac{0.4 \quad \text{cme}}{31.6\ \Omega/^{o}\text{C}} = 0.012\ ^{o}\text{C error} \tag{4}$$

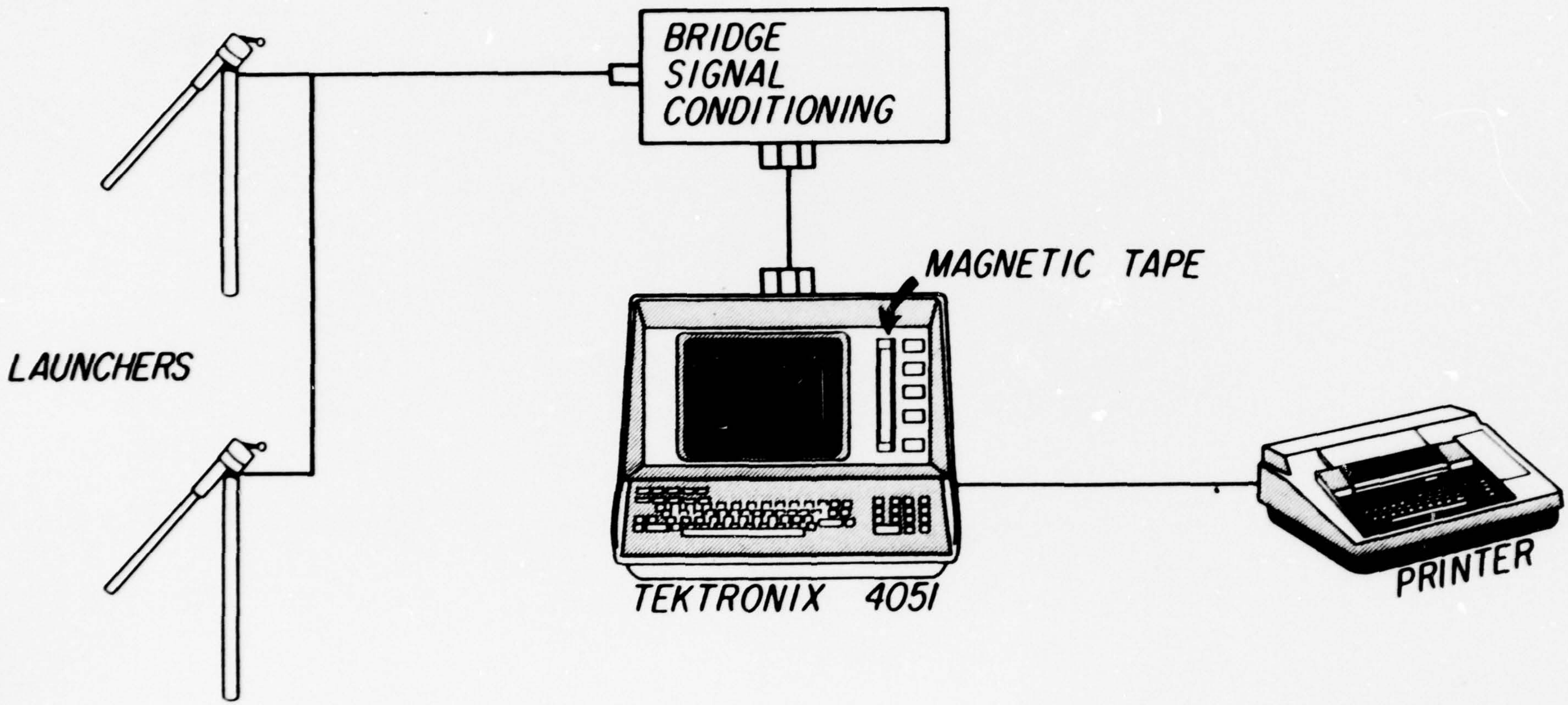
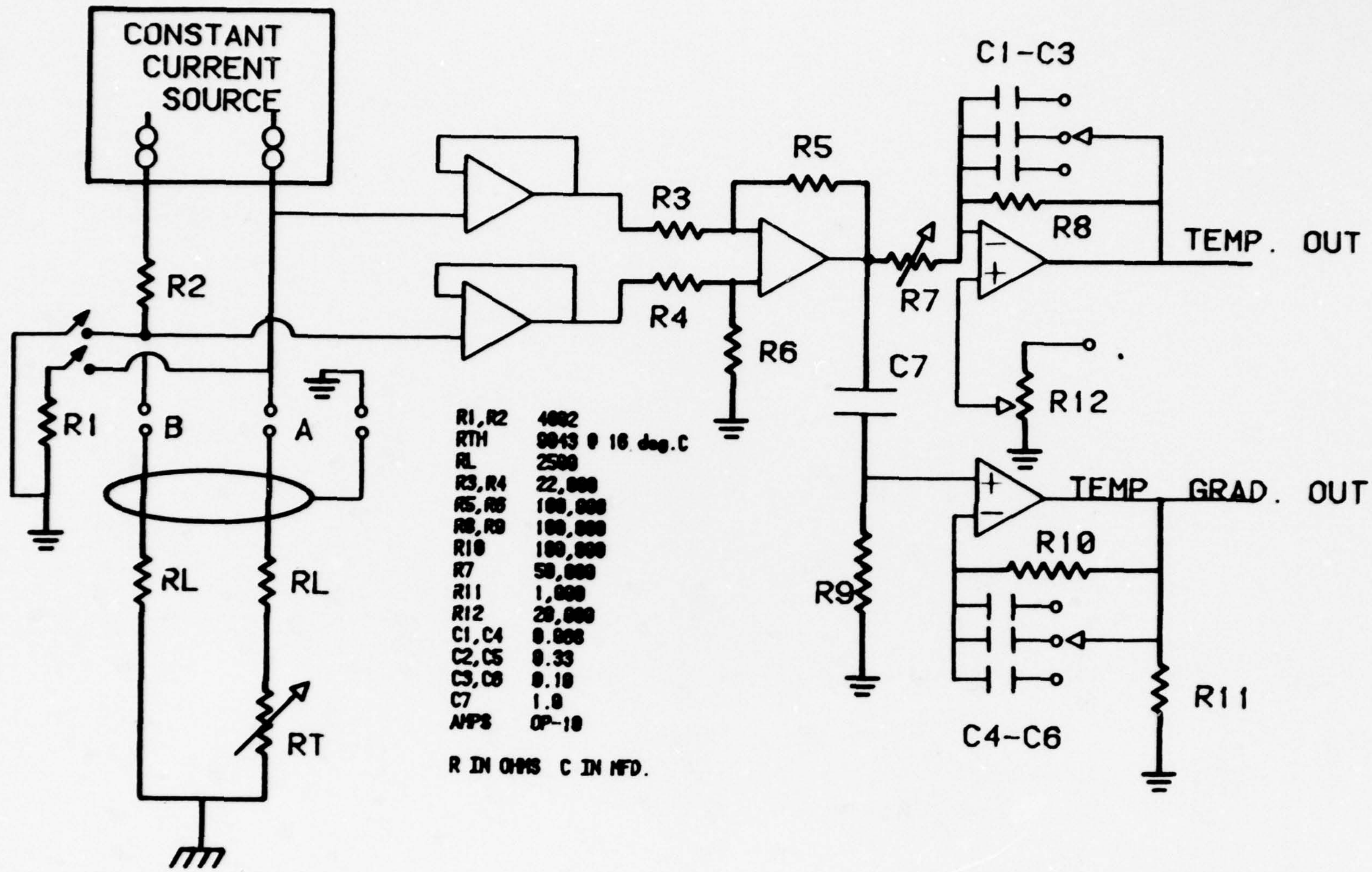

BRIDGE
SIGNAL
CONDITIONING
MAGNETIC TAPE
LAUNCHERS
TEKTRONIX 4051
PRINTER

FIGURE 1



R1,R2	4002
RTH	9043 @ 16 deg.C
RL	2500
R3,R4	22,000
R5,R6	100,000
R8,R9	100,000
R10	100,000
R7	50,000
R11	1,000
R12	20,000
C1,C4	0.068
C2,C5	0.33
C3,C6	0.10
C7	1.0
AMPS	OP-10

R IN OHMS C IN MFD.

FIGURE 2

For an eight bit data acquisition system scaled to cover a range of 12-28°C the least significant bit has a nominal weight of

$$\frac{16\ ^{o}C}{256\ bits} = 0.062\ ^{o}C/bit \tag{5}$$

Thus the equivalent error due to a 40000 ohm change in common mode resistance is equivalent to

$$\frac{0.012\ ^{o}C}{0.062\ ^{o}C/bit} = 0.19\ bit \tag{6}$$

Obviously any modulation of the common mode resistance by a 60 cycle shipboard power source would produce an additional error. In practice we found this was not difficult to eliminate. An additional problem which we did observe, however, was RF pickup on a launch cable which passed in the vicinity of a beacon transmitter on a buoy on deck of the ship. The induced RF signal could be detected by an oscilloscope but was well below the resolution of our data acquisition system. It is possible that in a higher resolution system, radar, voice transmitters or other transmissions could become a problem and that careful routing of cables would be required.

The signal conditioning circuits have severe constraints placed upon them in that the AC (temperature gradient) circuits attempt to measure signals down to the limits of state-of-the-art components. The signal conditioning circuits have an output of ±10 volts for a 16°C change in temperature and thus represent

20 volts/256 bits or 0.078 volts per bit of recorded signal. The amplifier gain of approximately 25 is low so that input noise and offset drift do not pose a problem in a quality amplifier (0.078 volt/bit/20=3.9 millivolts equivalent input offset errors). Indeed extending the resolution to 12 bits would not severely constrain the temperature amplifier since

$$\frac{20\ \text{volts}}{2096\ \text{bits}} = 0.00488\ \text{volt/bit} \tag{7}$$

and using a gain of 25, significant least-count noise would require equivalent input errors of

$$\frac{4.88\ \text{mV}}{25} = 195\mu\ \text{V} \tag{8}$$

well within the specification of an operational amplifier such as the OP 10. The previously mentioned sources such as common mode error, RF and AC pickup would probably exceed the noise contribution of this amplifier.

Due to the errors from absolute calibration of the thermistor and its stability with time (some unexplained degradation has been observed when XBTs are stored above room temperature for long periods of time), the 12 bit system is best used to extend the dynamic range rather than to increase accuracy. Our system as configured for the LDE experiment was limited to a 16°C range to optimize the resolution and accuracy and was adequate for the POLYMODE environment.

The temperature gradient measurement on the other hand is

much more demanding. Our circuit uses a gain of 3000 within the 3 db pass band of .1 Hz to 40 Hz with additional high frequency switchable cutoffs of 25 Hz and 8 Hz. The equivalent input errors thus become (for 1 bit of error on our 256 bit full scale range)

$$\frac{0.072 \text{ mV/bit}}{3000 \text{ (gain)}} = 26\mu \text{ V/bit} \tag{9}$$

Assuming good management of common mode, RF shielding and grounding techniques, this poses no problem for a good ac amplifier such as the OP07. However, for a 12 bit system,

$$\frac{4.88 \text{ mV/bit}}{3000 \text{ (gain)}} = 1.6\mu \text{ V/bit} \tag{10}$$

is the least count error and is barely achievable with this amplifier and dictates careful consideration to the above-mentioned error sources. We have chosen to use the additional dynamic range of the 12 bit system to increase the upper range of our signals rather than to improve resolution at the lower temperature scales as this allows working in all areas of the oceans. The relative performance of the 8 and 12 bit systems are shown in Table 1.

Tests Conducted

The following tests were conducted to establish the accuracy, reproducibility and noise performance of the XBT fine scale recording system:

	8 BIT SYSTEM	12 BIT SYSTEM
TEMP.RANGE		
DC	12.0.TO 28.0 deg C(16deg)	0.0 deg C TO 30.0 deg C (30 deg)
AC	+/-0.051 +/-0.105 deg C	+/-0.075 deg C TO +/- 0.276 deg C
RESOLUTION		
DC	0.10 TO 0.06 deg C	0.012 deg C TO 0.007 deg C
AC	0.00041 TO 0.00020 deg C	.000036 deg C TO 0.000134 deg C
ACCURACY	+/- 0.1 deg C(MANUF. CALIB.)	+/- 0.1 deg C (MANUF. CALIB.)
NOISE		
DC	0.025 deg C RMS MAX.	0.025 deg C RMS MAX.
AC	<.0004 deg C <.0002 deg C	UNKNOWN
AMP. GAIN		
DC	27	8.7
AC	3026	1000

TABLE 1

1) On deck test of standard T-11 to determine 60 Hz pickup of cable, launcher and XBT.

2) Resistor replacement of thermistor to determine stability and noise of unreeling spools of wire. 2 drops.

3) An oscillator replacing the thermistor to determine the spectral attenuation of high rate of change signals. 2 drops.

4) Alumina backed thermistor replacement of standard thermistor to determine feasibility of extending fine scale range of an XBT and establish roll-off of the standard thermistor. 1 drop.

5) Same as #4 except with 0.020" glass bead thermistor. 2 drops.

6) T-7 and T-7 simultaneous drop for fall rate consistency. 4 drops.

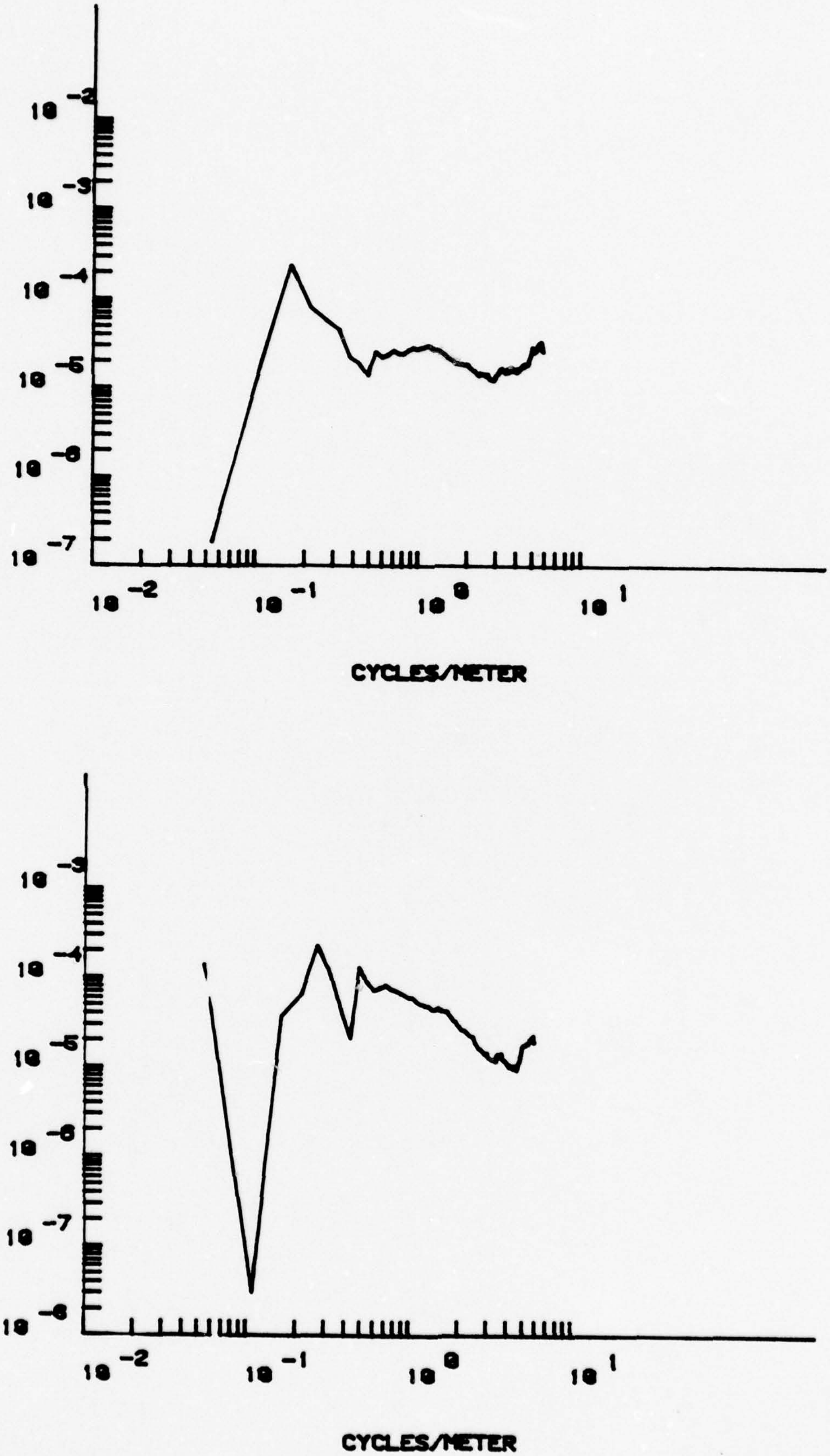
7) T-11 and T-11 simultaneous drops as #6 but with CTD casts for accuracy check. 4 drops.

Results of Tests

Test #1. Two spectra are shown in Figure 3 from a series of 256 point FFTs taken during a 7-minute sample.

Test #2. No signal was present during this drop indicating no contribution from unreeling effects.

Test #3. In this test a circuit was built which consisted



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}
10^{1}
CYCLES/METER
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-2}
10^{-1}
10^{0}
10^{1}
CYCLES/METER

FIGURE 3

of a precision resistor with a field effect transistor and resistor in series shunting the precision resistor. The FET was driven into conductance 10 times per second for a period of .015 seconds. The effect of this was to change the resistance of the parallel combination of the precision resistor and the FET resistor to a lower value. The turn on was sharp and the turn off determined by an R-C time constant (See Figure 4). This circuit replaced the thermistor in a standard XBT probe and was sampled at a 1 KHz rate intermittently over the 7-minute time of a T-11 drop. The spectra of several segments of the 7-minute sample is shown in Figure 5 and shows no significant change in attenuation below 100 Hz as the two reels of wire pay out (less than 2 db). This fact is important if one is to use the standard XBT system to resolve high frequency variations (fine scale structure) from a standard XBT.

Test #4. In this test the standard disc thermistor was replaced by a .05 x .05 x .01 inch alumina backed thermistor which was insulated with a .002 inch glass coating on the thermistor side of the substrate. Laboratory dip tests indicated that this thermistor had a 2-4 times faster response than the standard disc thermistor. This unit was dropped simultaneously with a standard T-11 and the time series plots and spectra of the high passed temperature gradient were compared. The results are shown in Figure 6 for the analog plot and 6A for the spectra.

Test #5. Figure 7 shows the analog data on 0.020 inch glass coated bead thermistor in the same test as Test #4.

Test #6. In this test, two T-7 XBTs were dropped

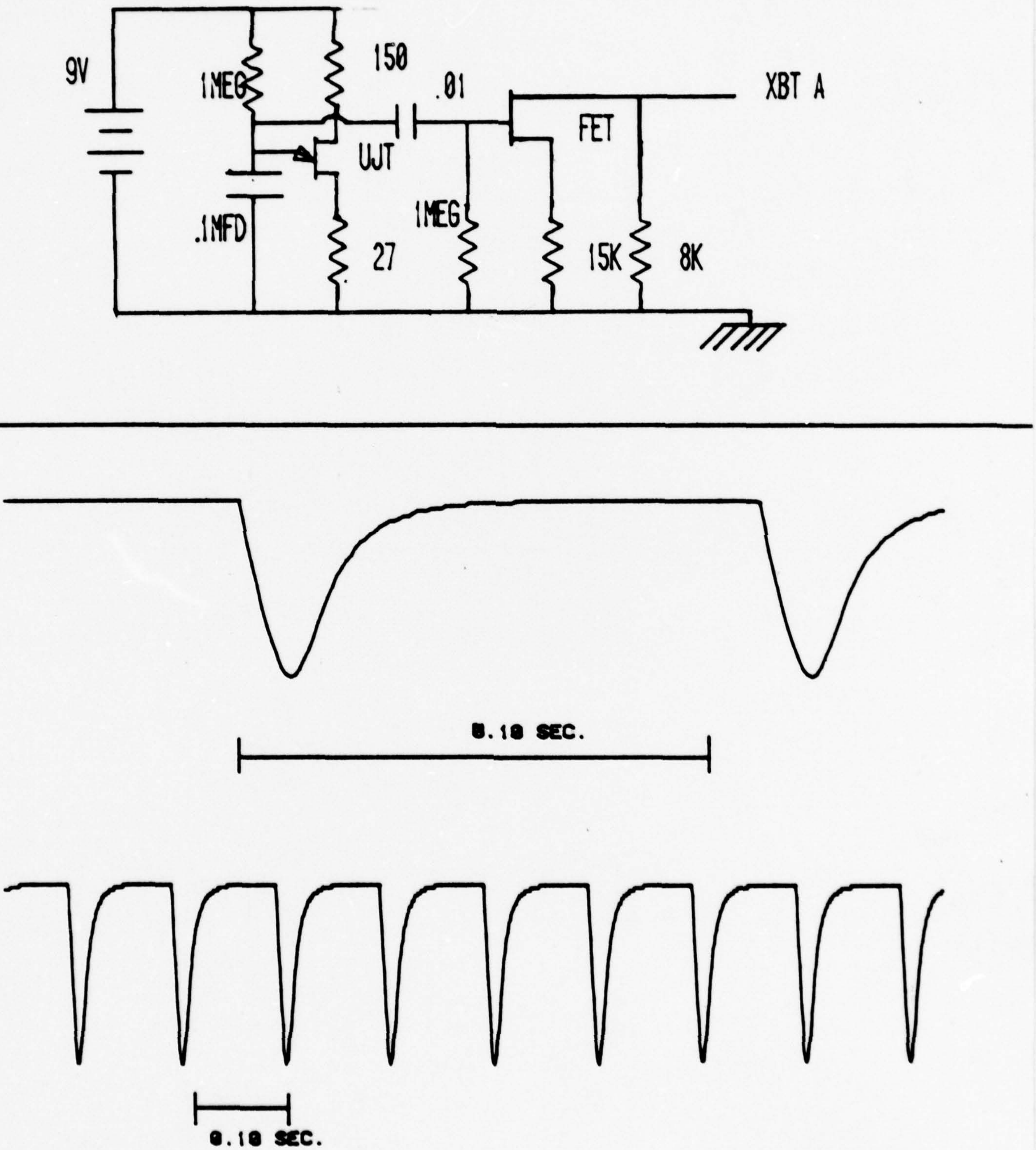


FIGURE 4

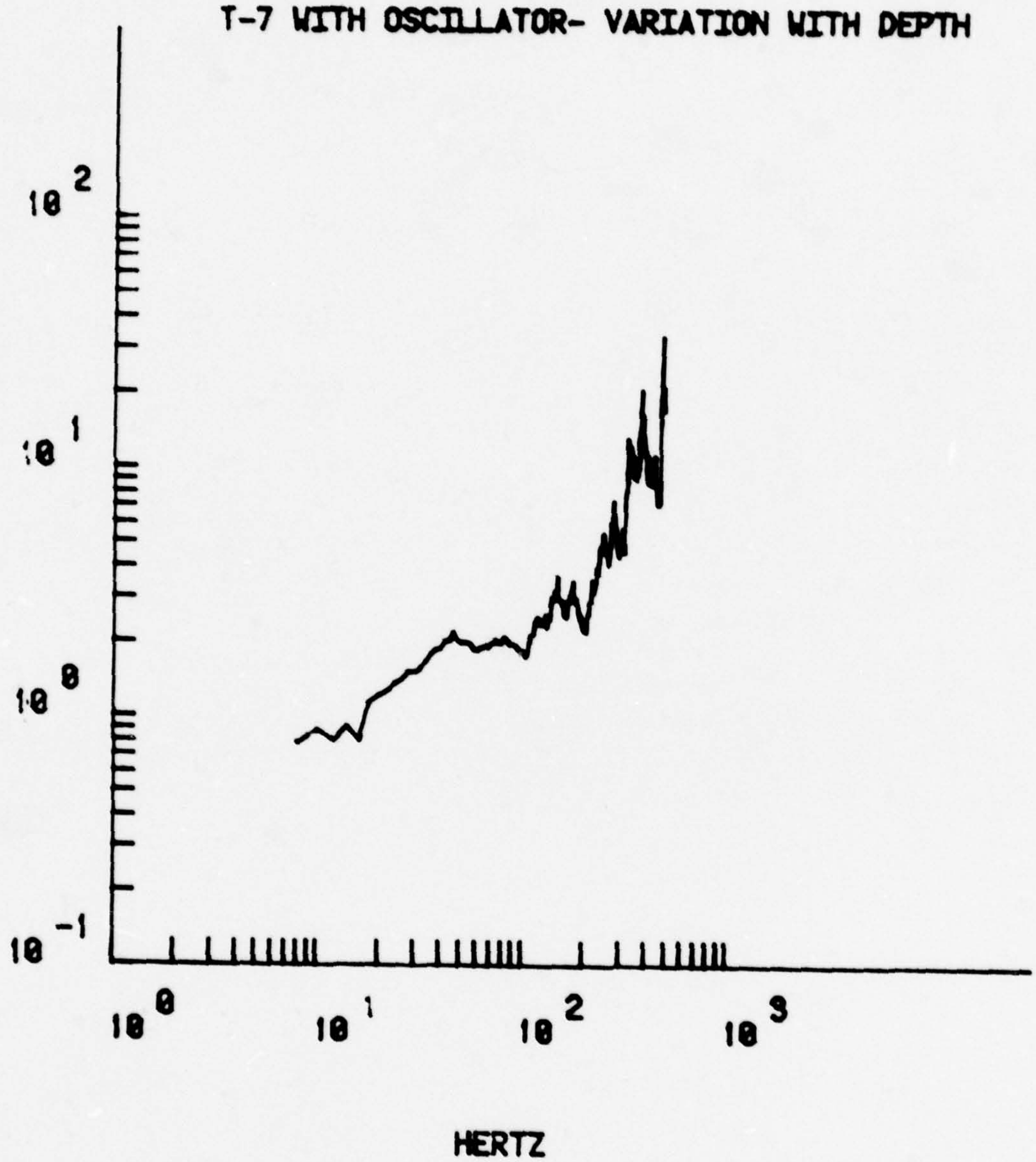

T-7 WITH OSCILLATOR- VARIATION WITH DEPTH
10 2
10 1
10 0
10 -1
10 0
10 1
10 2
10 3
HERTZ

FIGURE 5

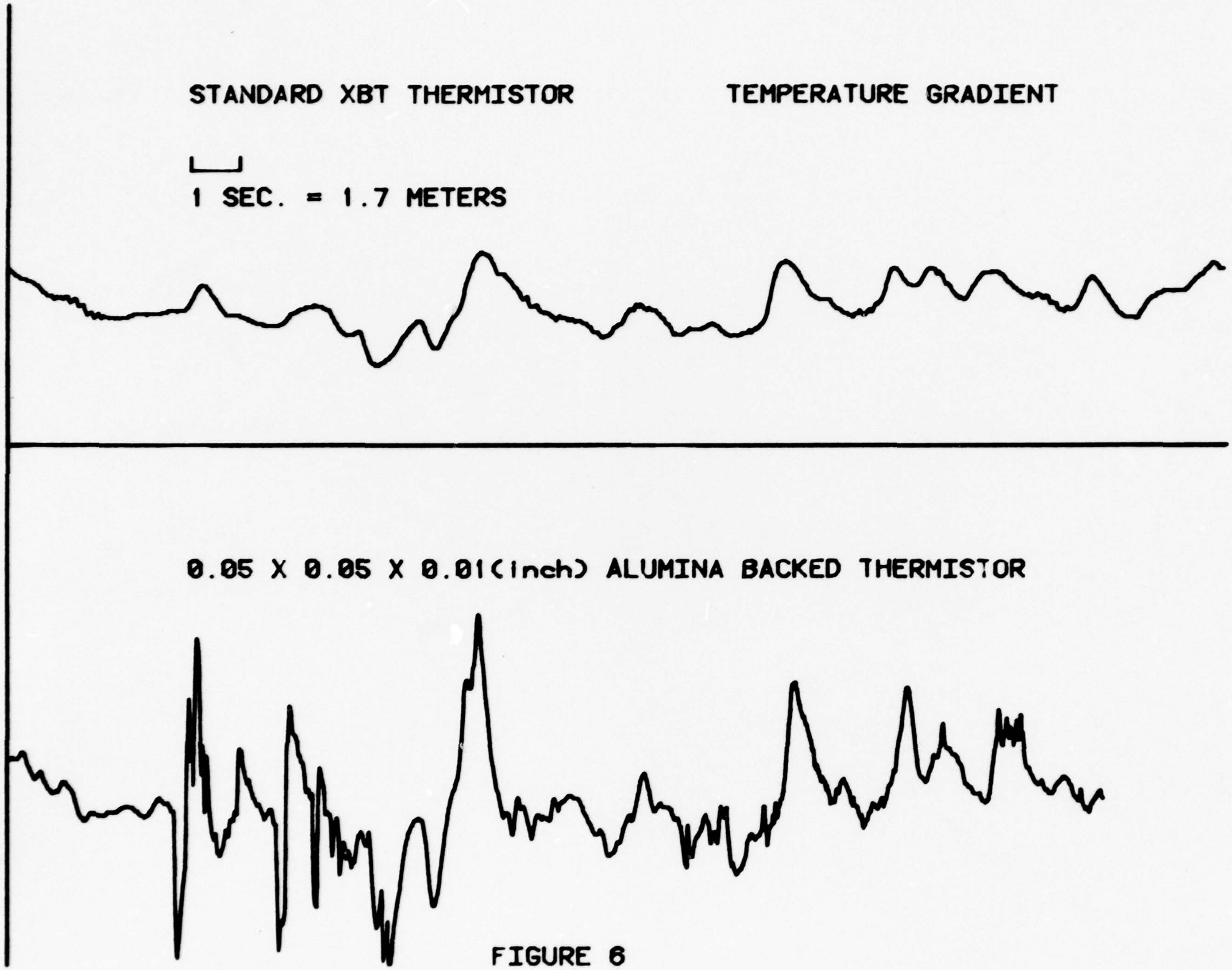
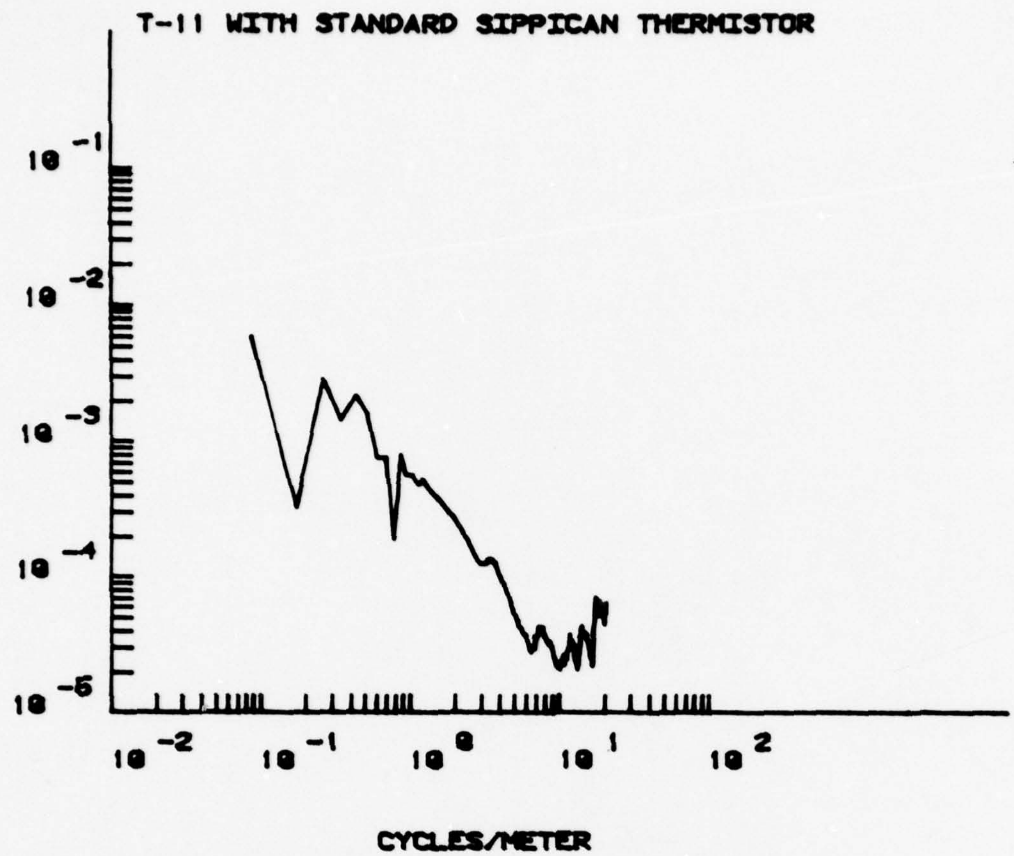
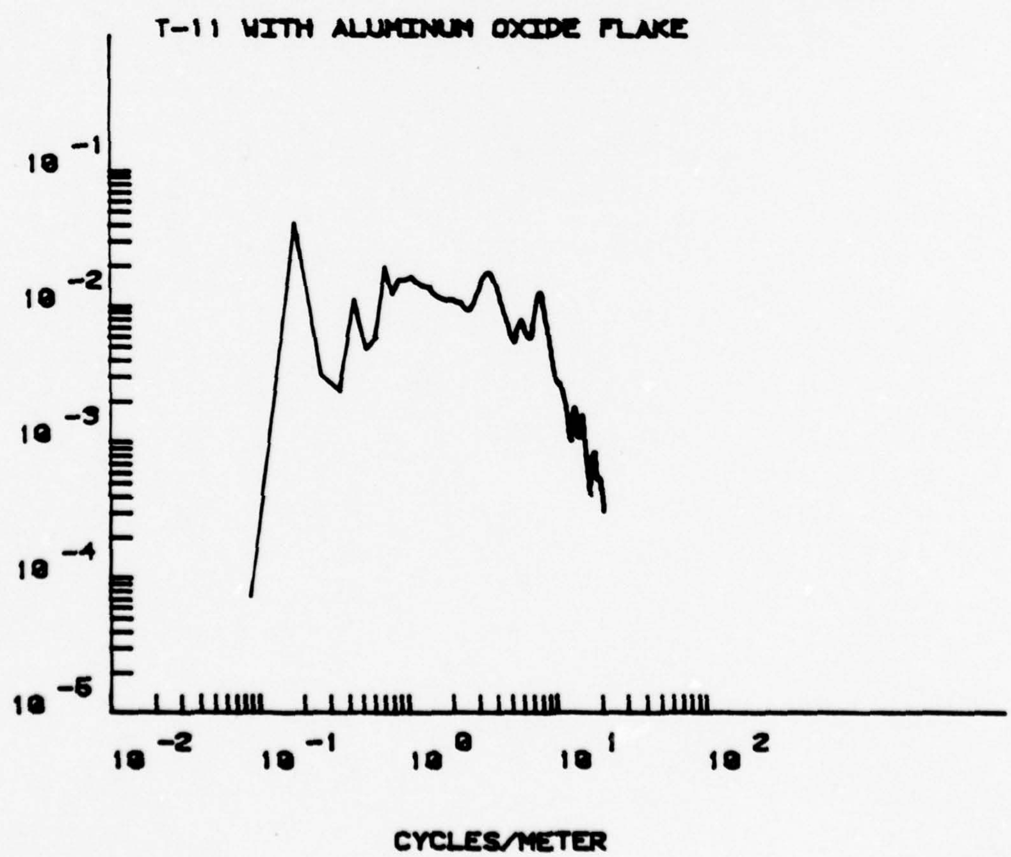

STANDARD XBT THERMISTOR
TEMPERATURE GRADIENT
1 SEC. = 1.7 METERS
0.05 X 0.05 X 0.01(inch) ALUMINA BACKED THERMISTOR

FIGURE 6



T-11 WITH STANDARD SIPPICAN THERMISTOR
10 -1
10 -2
10 -3
10 -4
10 -5
10 -2
10 -1
10 0
10 1
10 2
CYCLES/METER



T-11 WITH ALUMINUM OXIDE FLAKE
10 -1
10 -2
10 -3
10 -4
10 -5
10 -2
10 -1
10 0
10 1
10 2
CYCLES/METER

FIGURE 6A

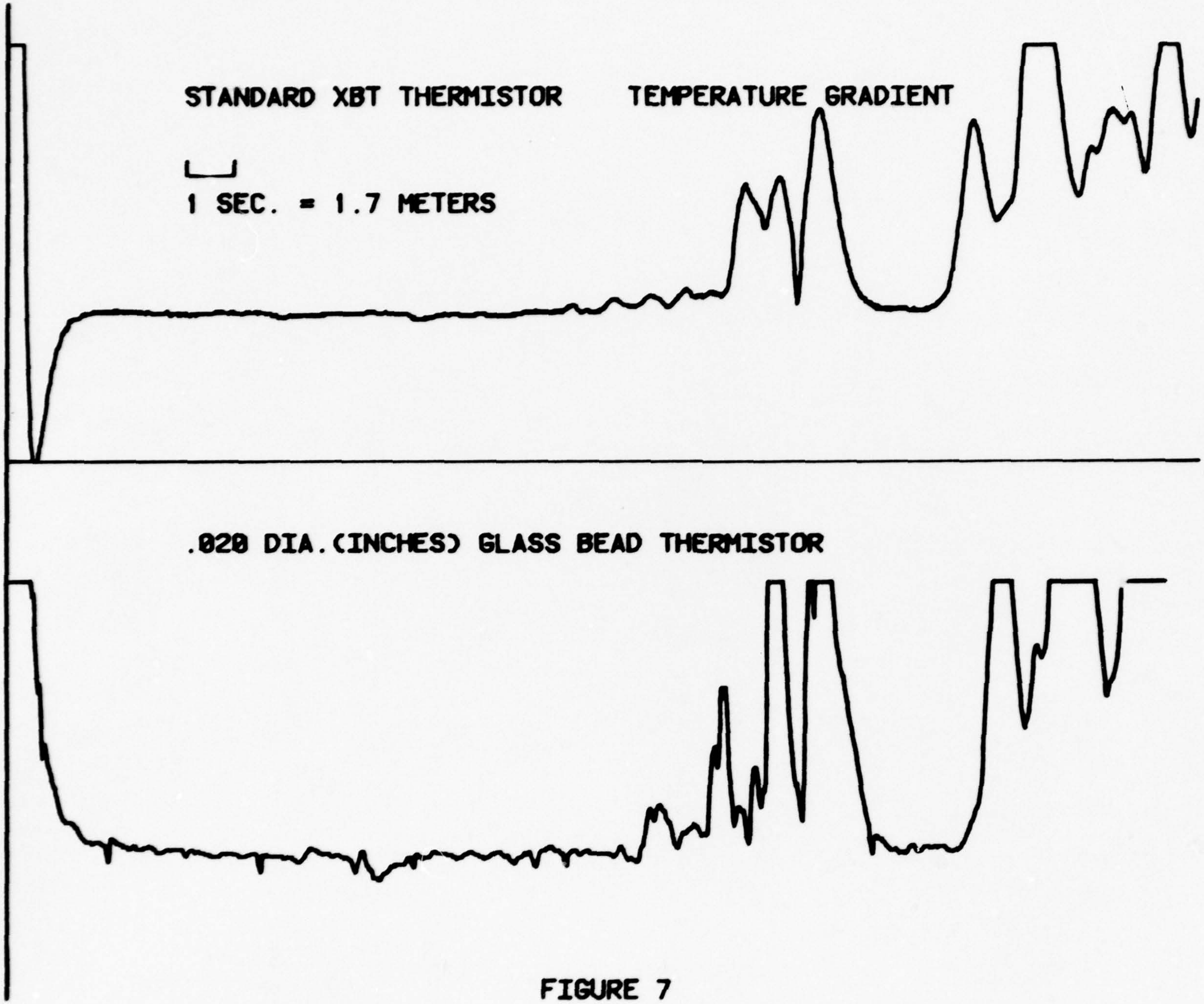

STANDARD XBT THERMISTOR
TEMPERATURE GRADIENT
1 SEC. = 1.7 METERS
.020 DIA.(INCHES) GLASS BEAD THERMISTOR

FIGURE 7

simultaneously with Unit #1 used as the trigger to commence recording. The first 415 meters are shown on the top trace and the last 335 meters are shown on the bottom of Figure 8. The numbers associated with various features represent the number of samples from the start of recording on Unit #1 and relate to time as #/~~10~~ 25 in seconds. If the offset at the start of recording is subtracted from Unit #2, the time separation is 22 or 22/25 seconds or spatially 5.54 meters based on a fall rate of 6.3 meters per second. 5 drops were made with two T-7s and the maximum differences were 7.5 meters with a mean difference of 5.2 meters.

Test #7. This test was an actual survey of an active front made during a 14.5 hour time period. Two T-11s were dropped every 15 minutes with a ship speed of approximately 4 knots. The sample rate was 15 samples per second with an 8 Hz filter applied to the signal. In addition to this test, four T-11 - T-11 drops were made at 0, 4, 8, 10 knots and one T-11 - T-11 drop was made at a sample rate of 200 samples per second with no filter applied. Figures 9 and 10 show isotherm stabilities for 5, 10, 20, 50 meters during the T-11 - T-11 front survey. This method was used to confirm the calibration accuracy of the XBT's and the stability of the signal conditioning circuits. At no time during the 12.5 hour period did the temperatures of the two XBTs launched simultaneously depart from one another by more than 0.1°C. Apparently, the shallower isotherms changed very little over this period.

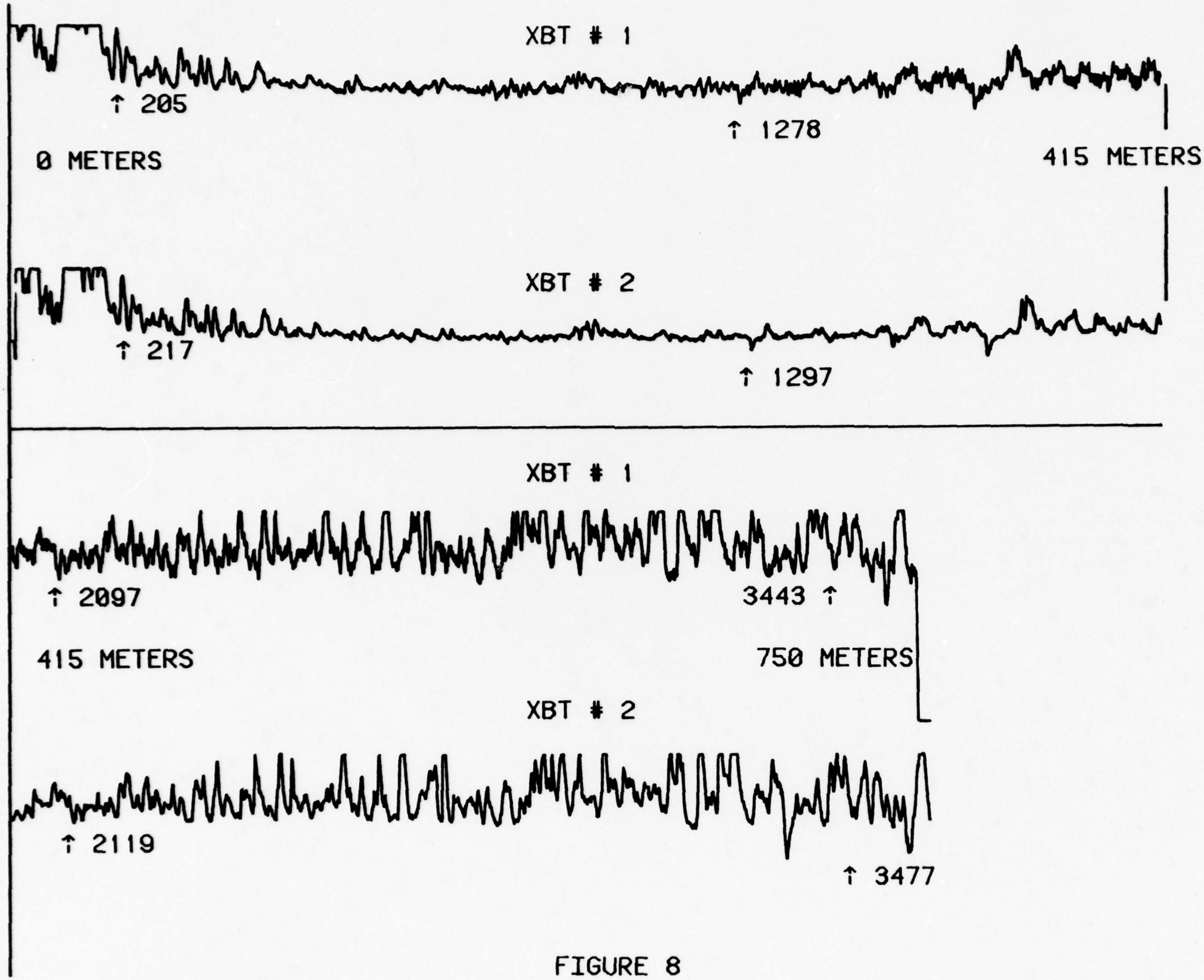
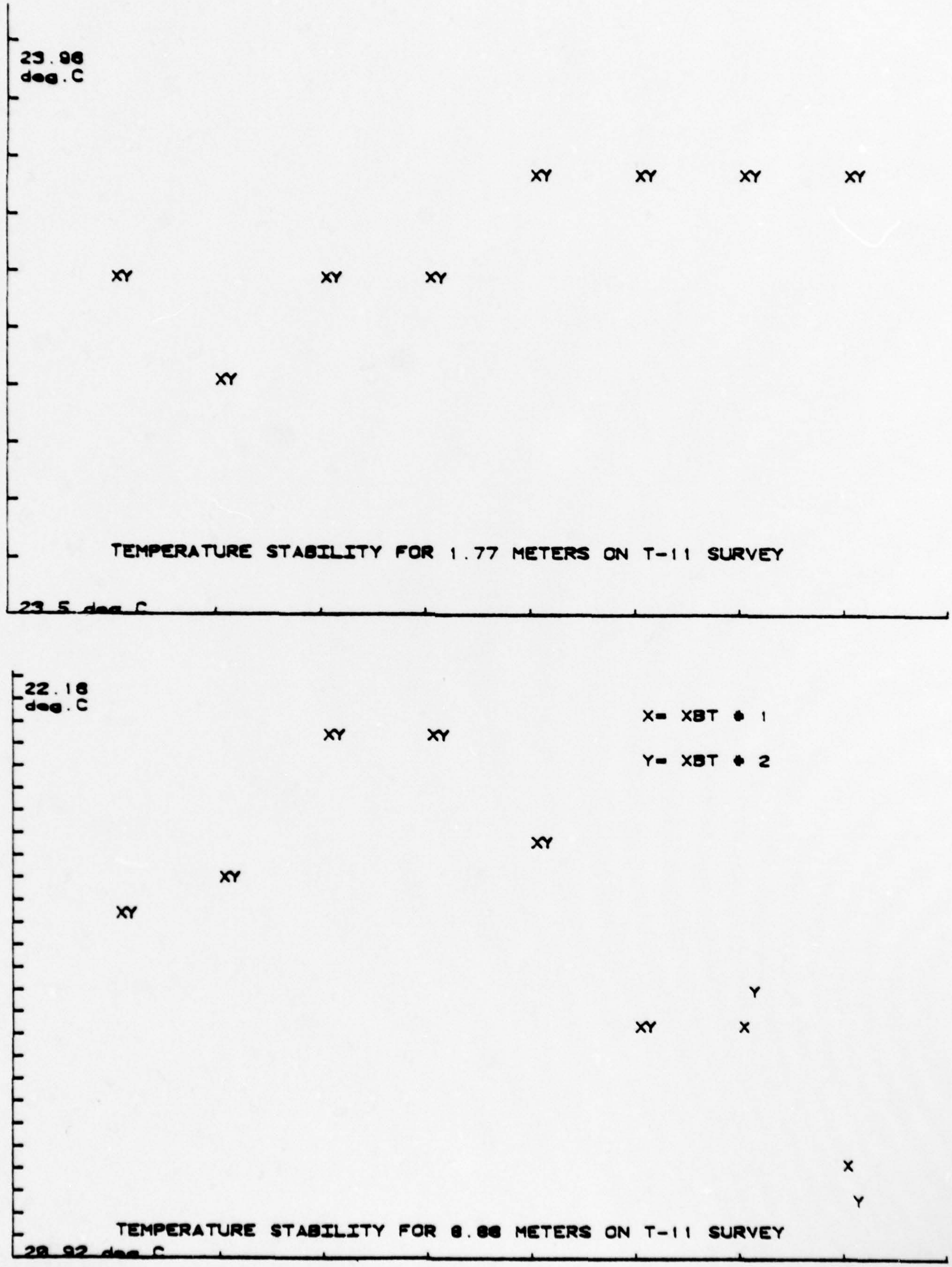
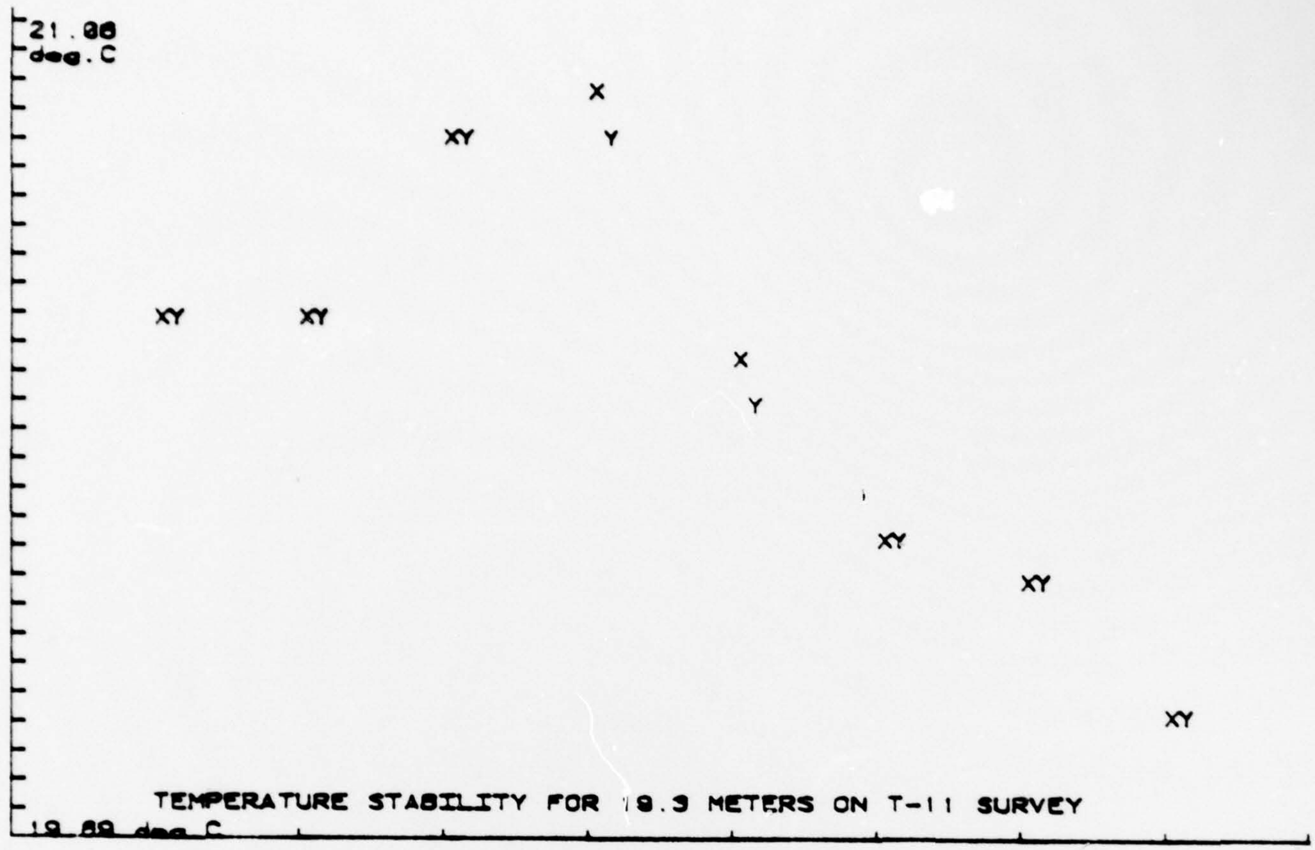

XBT # 1
↑ 205
↑ 1278
0 METERS
415 METERS
XBT # 2
↑ 217
↑ 1297
XBT # 1
↑ 2097
3443 ↑
415 METERS
750 METERS
XBT # 2
↑ 2119
↑ 3477

FIGURE 8



23.98
deg.C
XY
TEMPERATURE STABILITY FOR 1.77 METERS ON T-11 SURVEY
23.5 deg.C
22.16
deg.C
X= XBT # 1
Y= XBT # 2
XY
X
Y
TEMPERATURE STABILITY FOR 8.88 METERS ON T-11 SURVEY
20.92 deg.C

FIGURE 9


21.08
deg.C
TEMPERATURE STABILITY FOR 19.3 METERS ON T-11 SURVEY

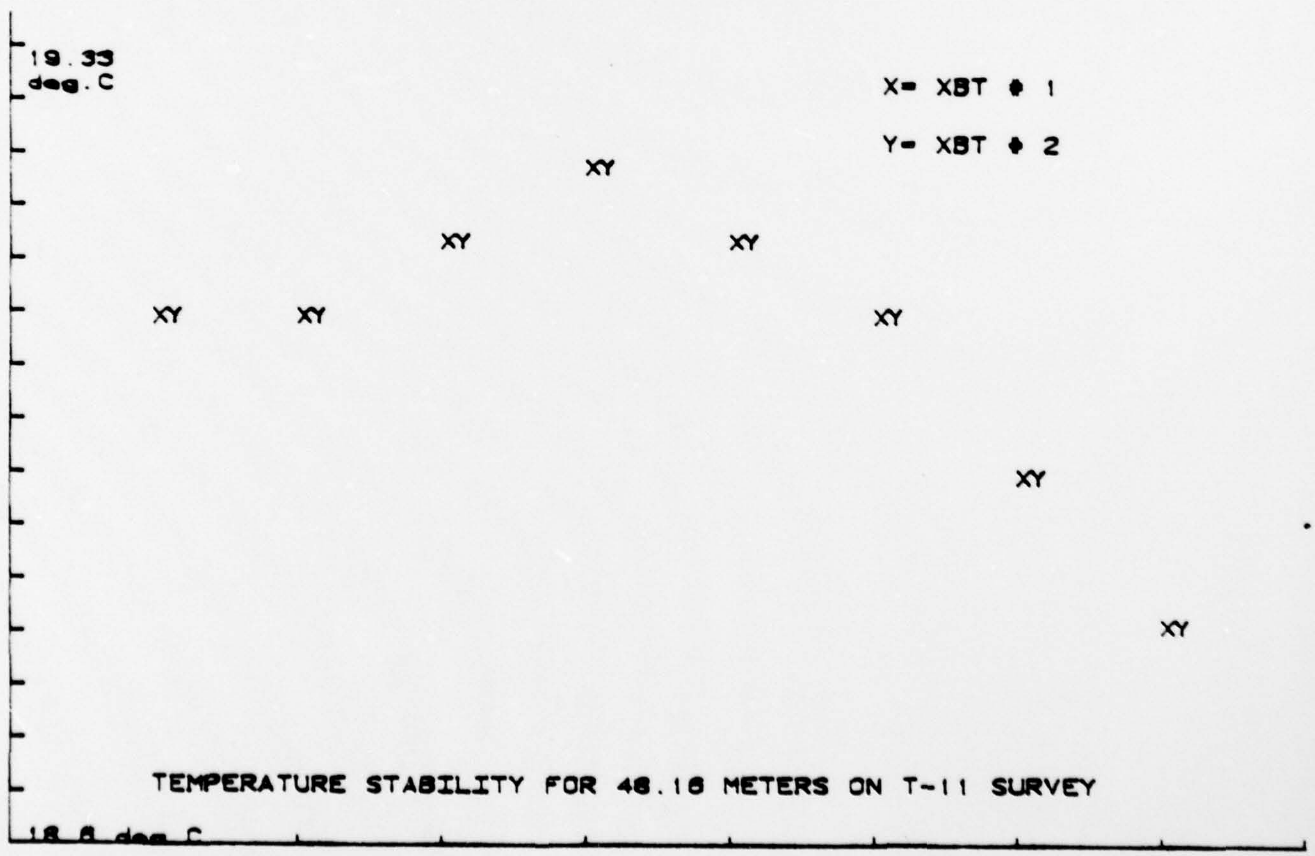

19.33
deg.C
X= XBT # 1
Y= XBT # 2
TEMPERATURE STABILITY FOR 48.16 METERS ON T-11 SURVEY

FIGURE 10

Additional work has been done to document the performance of the system hastily prepared for the POLYMODE LDE. A careful calibration of the 8 bit system was done to check the performance of the signal conditioning circuits and the performance of the data acquisition system. Figure 11 shows the linearity of the 8 bit D.A.S. and Figure 12 shows the linearity of the bridge circuit. The voltage from the signal conditioning circuits was measured as a function of ohms on the bridge and a linear least squares fit was calculated. Table 2 shows the voltage read versus the voltage calculated from the fit and the respective differences. Reconfiguration of the signal conditioning circuits to accept the Trans Era 12 bit data acquisition system was also accomplished and a linearity and stability check of the 12 bit system completed. The present Trans Era D.A.S. performs well only to 10 bit accuracy and linearity however the manufacturer claims to have improved this performace to 12 bits. The 12 bit system linearity is shown in Figure 13.

Additional Figures

Four T-11 drops are shown in Figures 14, 15, 16, and 17 and one T-7 drop is shown in Figure 18. The steppiness apparent in the 18.5° region is an artifact of the 8 bit .1°C resolution of the system. The sharp spike of the gradient channel is actually off scale. Both of these problems will be corrected with the 12 bit system. Finally, transfer functions for the 3-switch

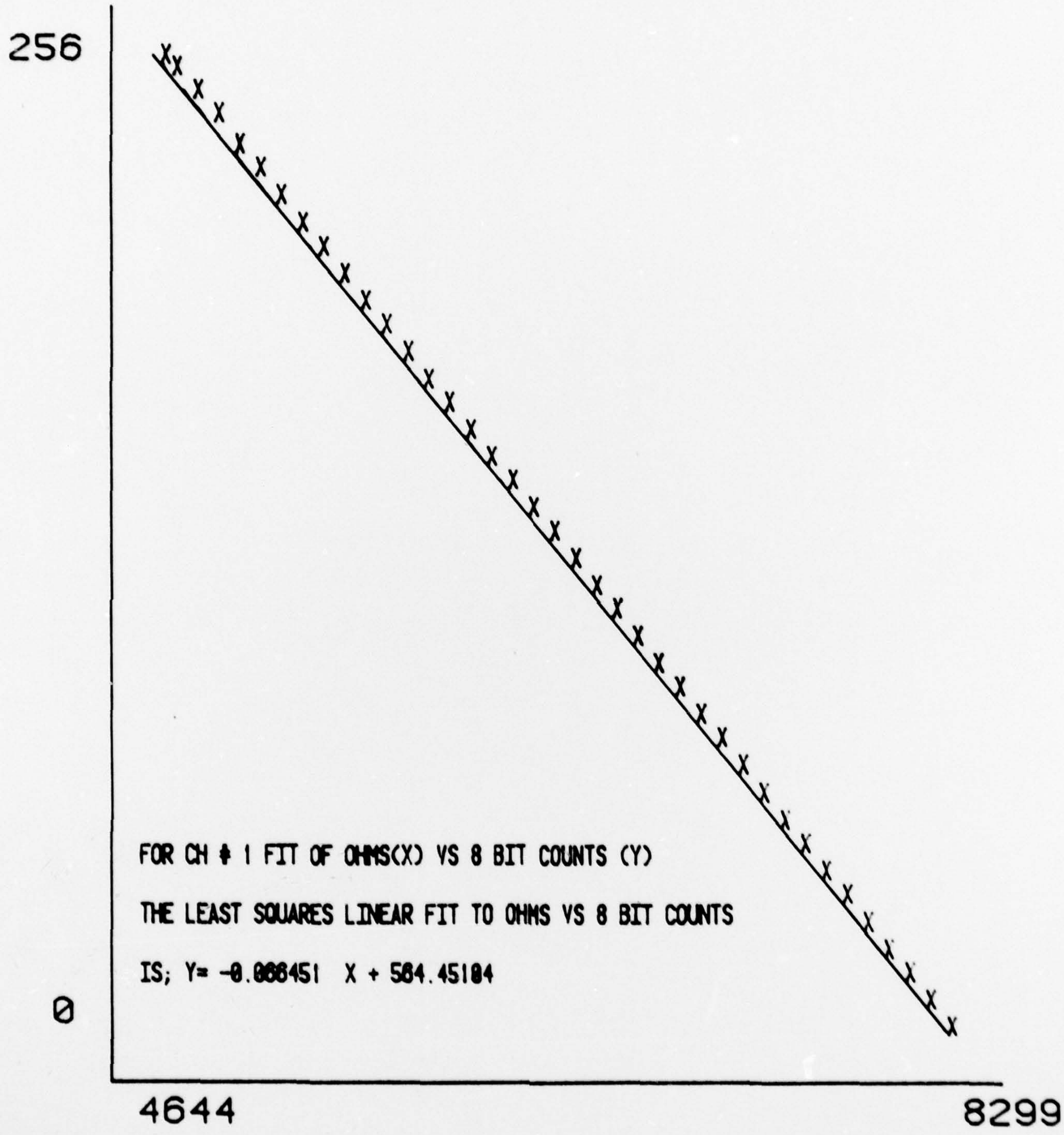

256
0
4644
8299
FOR CH # 1 FIT OF OHMS(X) VS 8 BIT COUNTS (Y)
THE LEAST SQUARES LINEAR FIT TO OHMS VS 8 BIT COUNTS
IS; Y= -0.068451 X + 564.45104

FIGURE 11

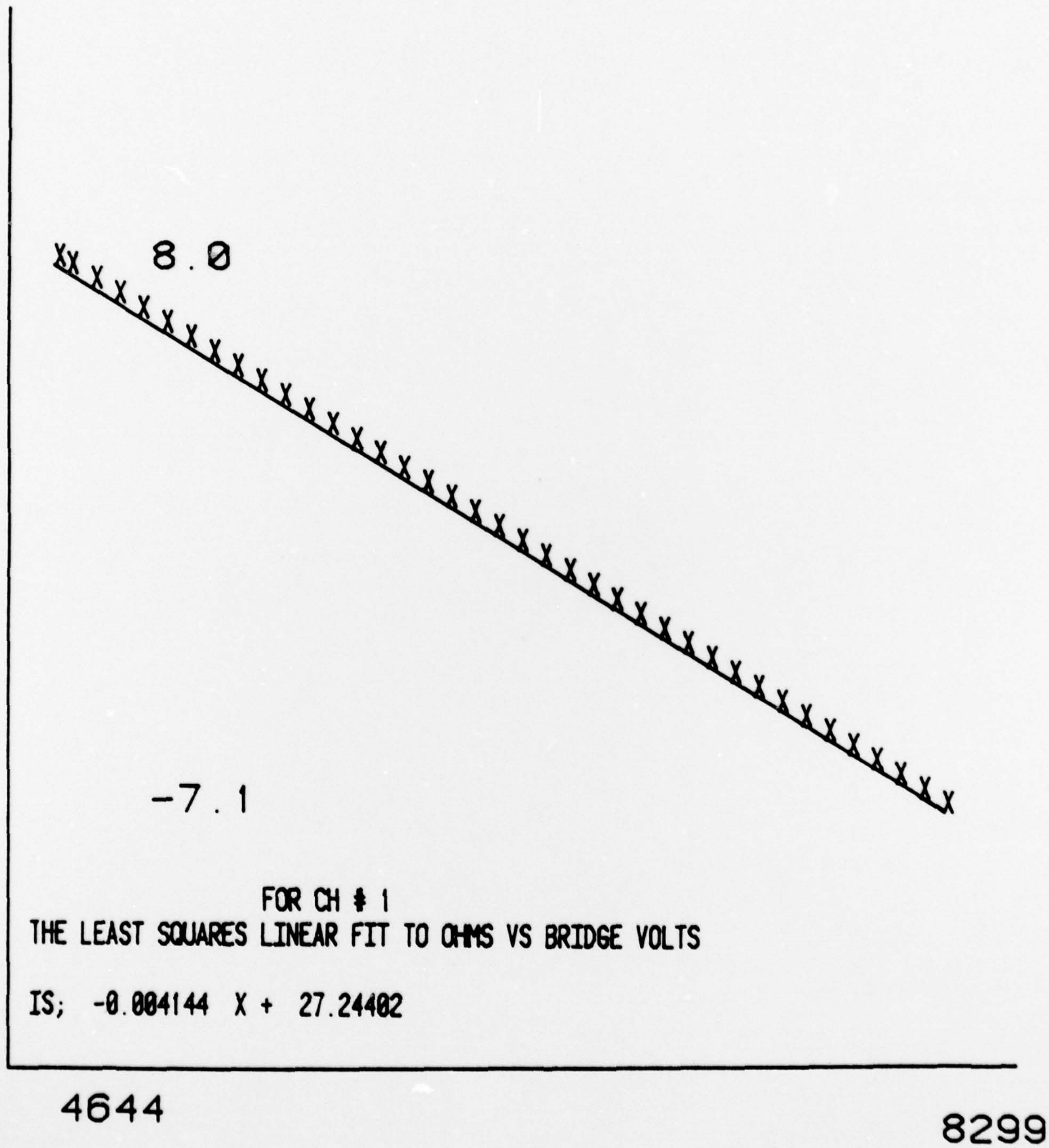

8.0
-7.1
FOR CH # 1
THE LEAST SQUARES LINEAR FIT TO OHMS VS BRIDGE VOLTS
IS; -0.004144 X + 27.24402
4644
8299

FIGURE 12

OHMS VS BRIDGE VOLTS

OHMS	VOLTS CALC.	VOLTS READ	DIFF.
4644.4	7.998	7.994	4.493E-003
4799.4	7.356	7.357	-1.404E-003
4999.3	6.528	6.529	-1.061E-003
5099.1	6.114	6.114	-2.179E-004
5299.2	5.285	5.285	-5.035E-004
5499.2	4.456	4.457	-6.748E-004
5699.2	3.627	3.628	-3.460E-004
5899.3	2.798	2.798	6.844E-005
6098.9	1.971	1.971	5.548E-004
6299.0	1.142	1.142	2.692E-004
6499.1	0.313	0.313	-2.164E-004
6699.1	-0.516	-0.516	1.238E-005
6899.2	-1.345	-1.345	-4.732E-004
7098.8	-2.172	-2.173	7.131E-004
7298.7	-3.001	-3.002	1.156E-003
7498.8	-3.830	-3.831	7.707E-004
7698.8	-4.659	-4.660	7.995E-004
7898.9	-5.488	-5.488	4.139E-004
8098.6	-6.315	-6.317	1.186E-003
8298.6	-7.144	-7.145	1.115E-003

TABLE 2

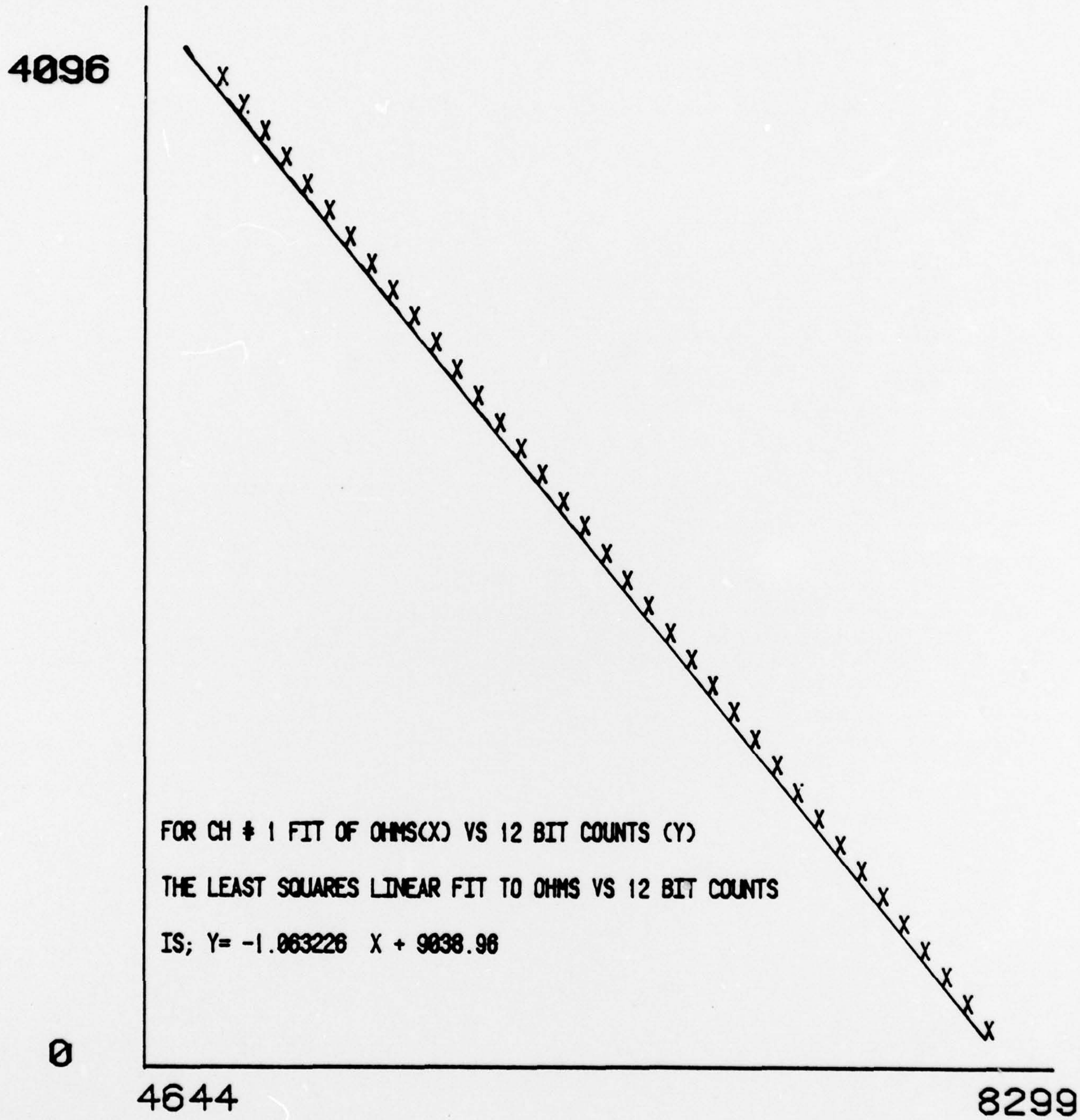

4096
0
4644
8299
FOR CH # 1 FIT OF OHMS(X) VS 12 BIT COUNTS (Y)
THE LEAST SQUARES LINEAR FIT TO OHMS VS 12 BIT COUNTS
IS; Y= -1.063226 X + 9038.96

FIGURE 13

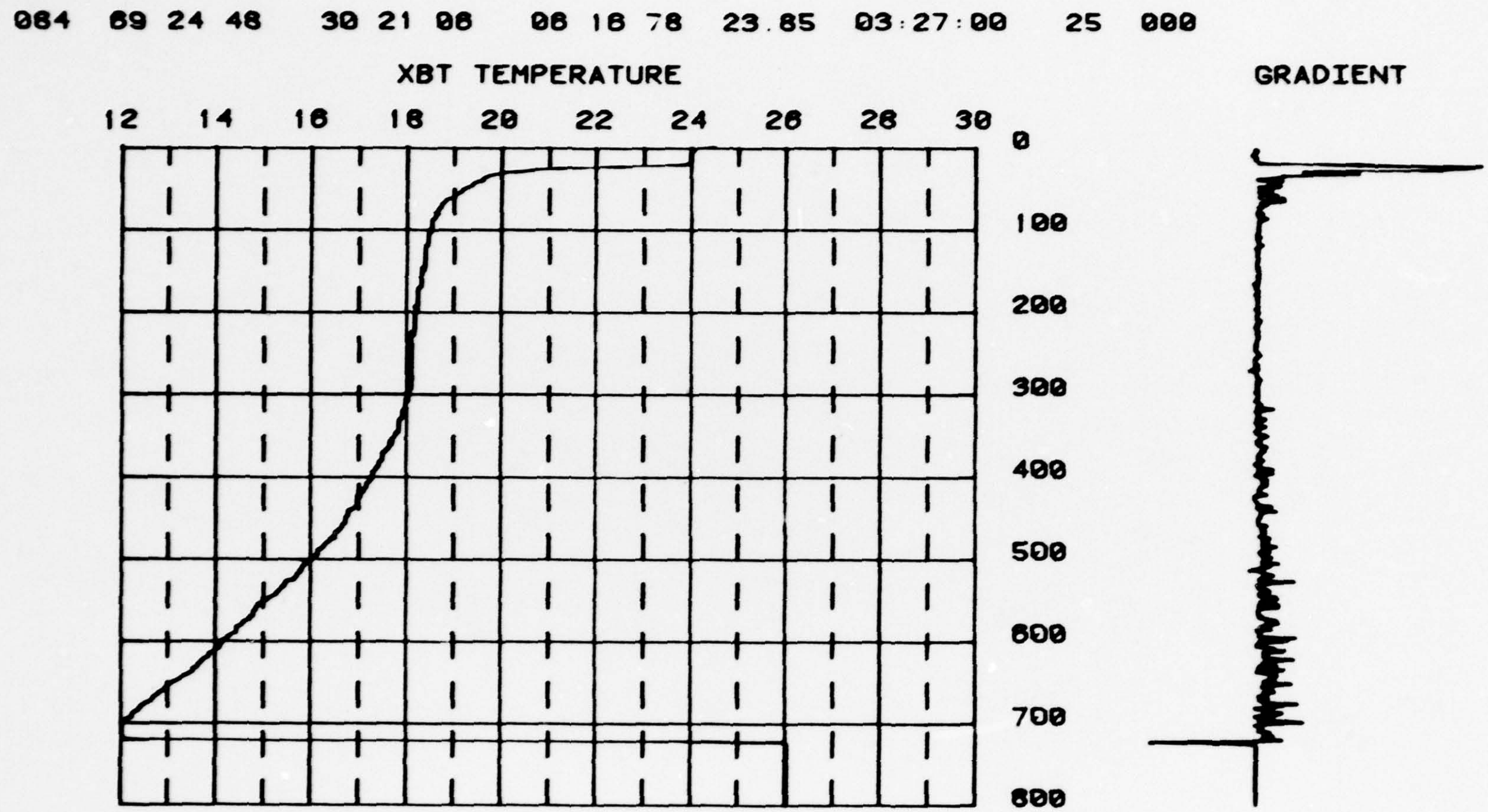

064 69 24 48 30 21 06 06 16 78 23.85 03:27:00 25 000
XBT TEMPERATURE
GRADIENT
12
14
16
18
20
22
24
26
28
30
0
100
200
300
400
500
600
700
800

FIGURE 14

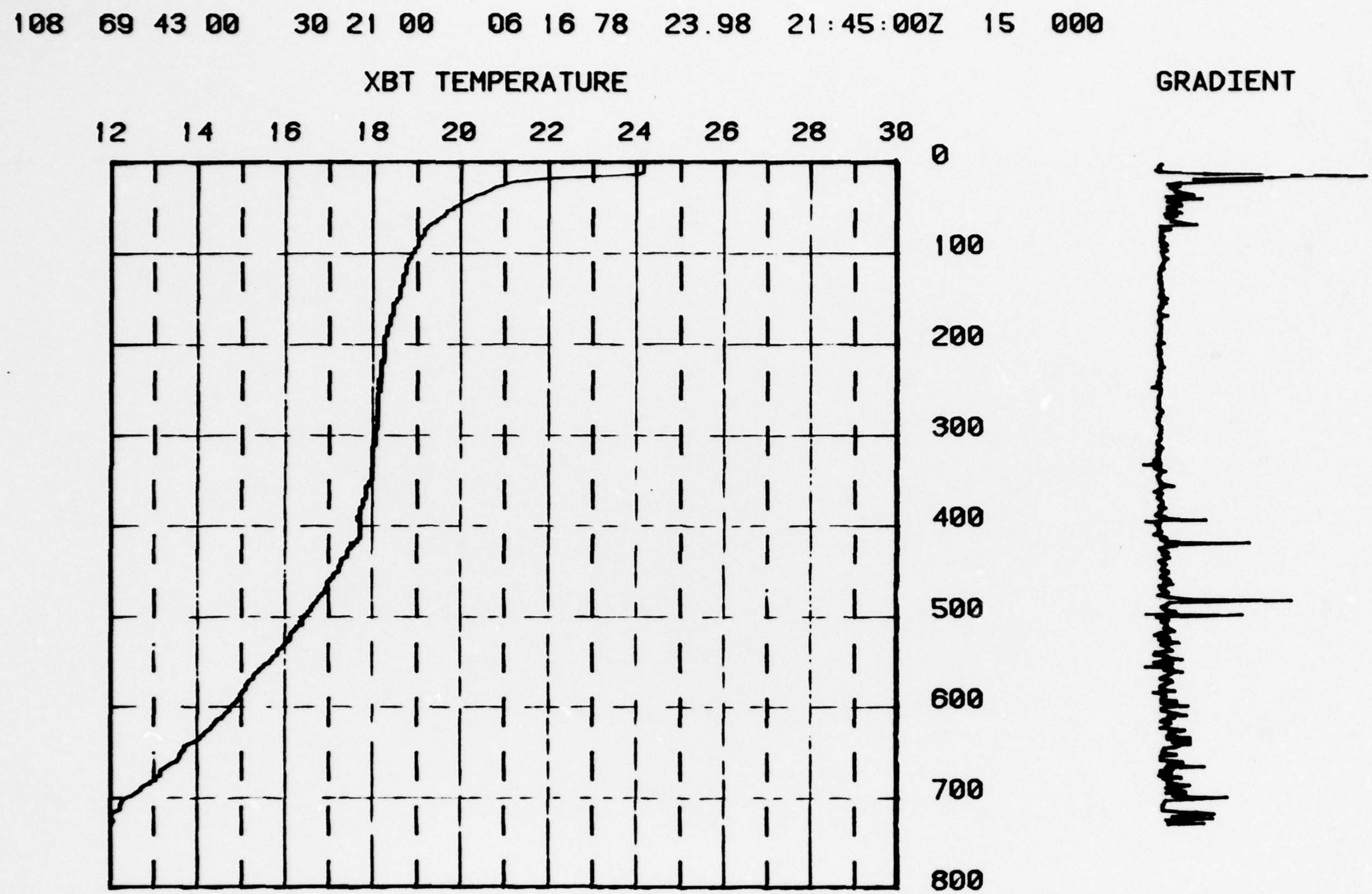

108 69 43 00 30 21 00 06 16 78 23.98 21:45:00Z 15 000
XBT TEMPERATURE
GRADIENT
12
14
16
18
20
22
24
26
28
30
0
100
200
300
400
500
600
700
800

FIGURE 15

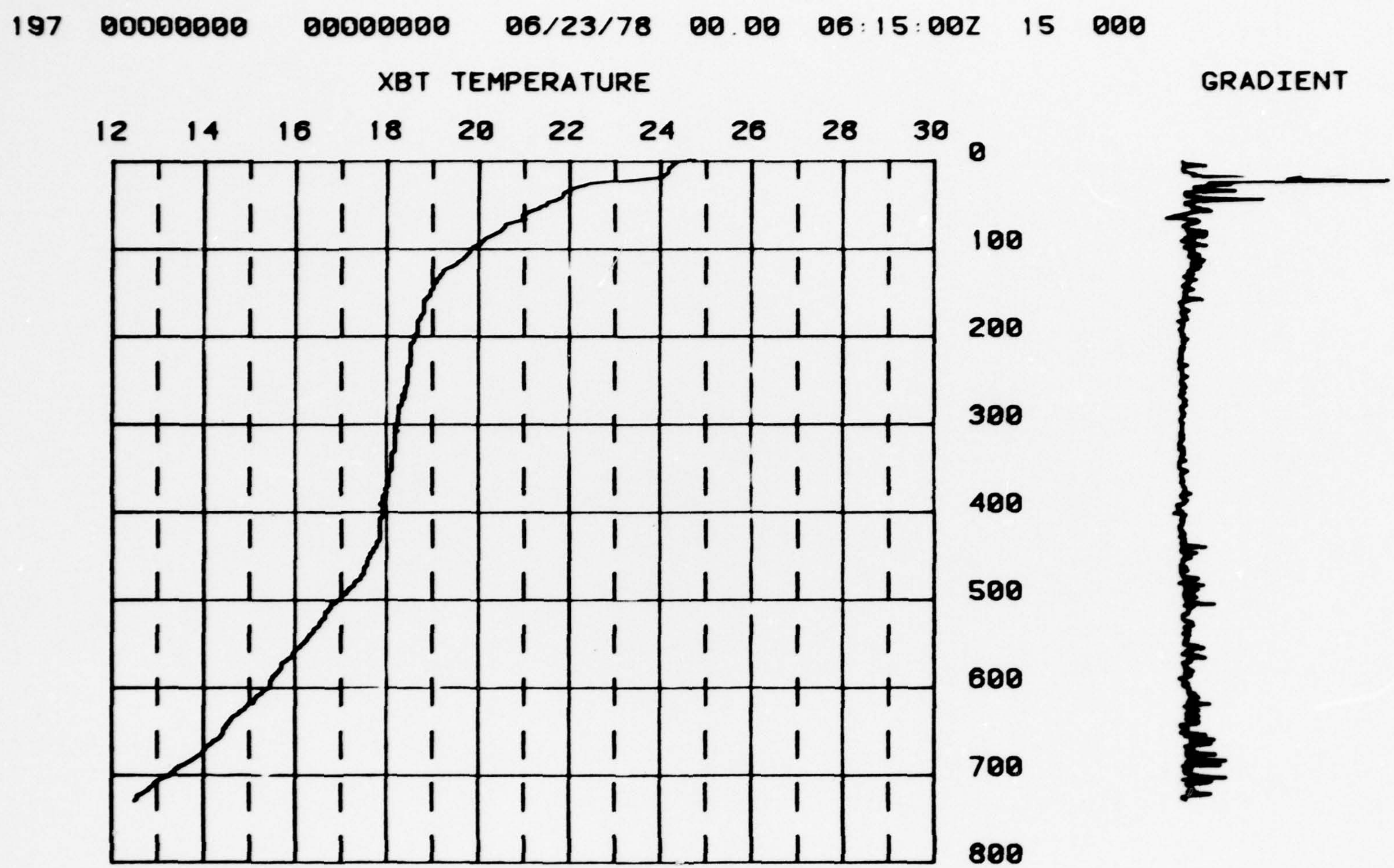

197 00000000 00000000 06/23/78 00.00 06:15:00Z 15 000
XBT TEMPERATURE
GRADIENT
12 14 16 18 20 22 24 26 28 30
0 100 200 300 400 500 600 700 800

FIGURE 16

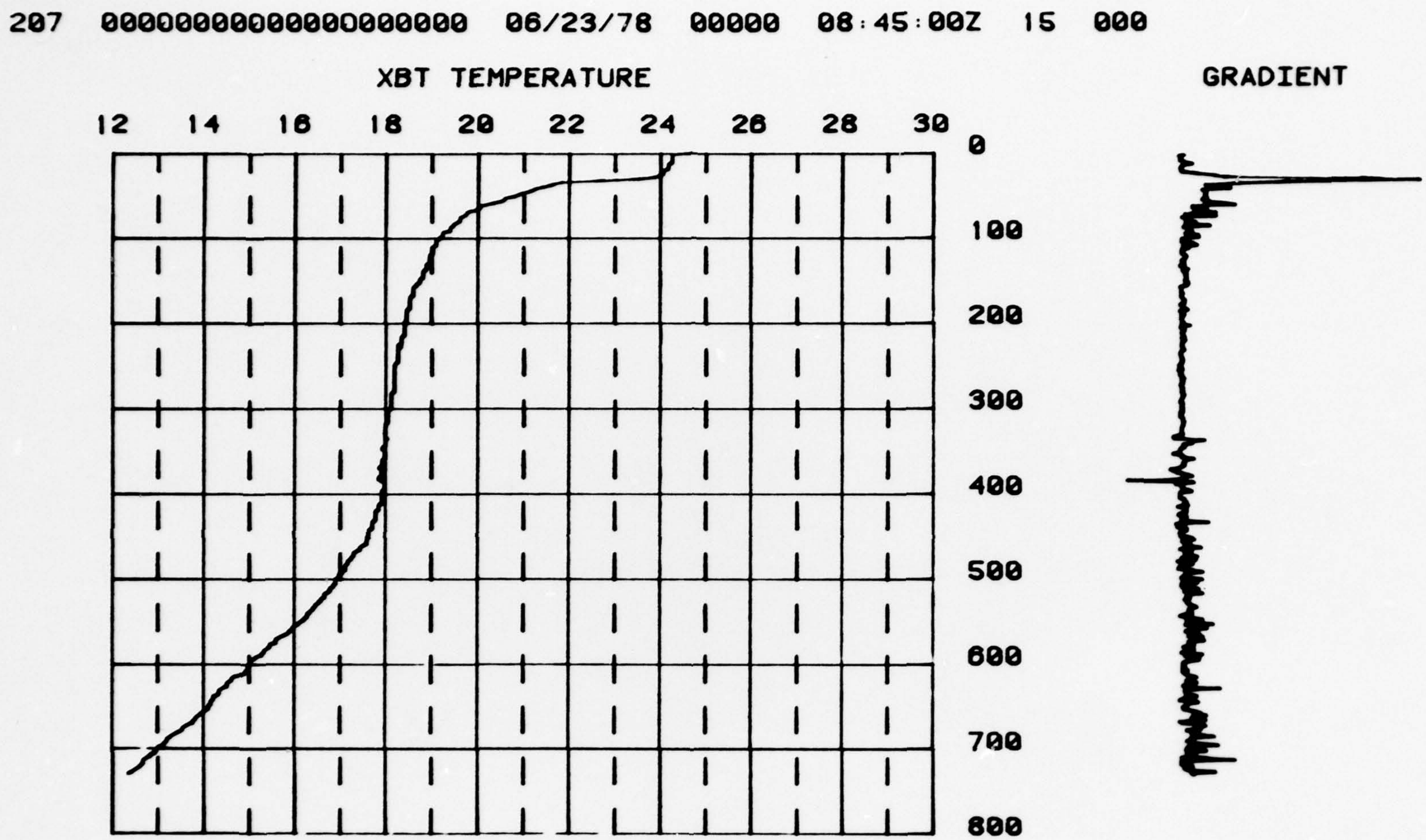

207 0000000000000000000 06/23/78 00000 08:45:00Z 15 000
XBT TEMPERATURE
GRADIENT
12
14
16
18
20
22
24
26
28
30
0
100
200
300
400
500
600
700
800

FIGURE 17

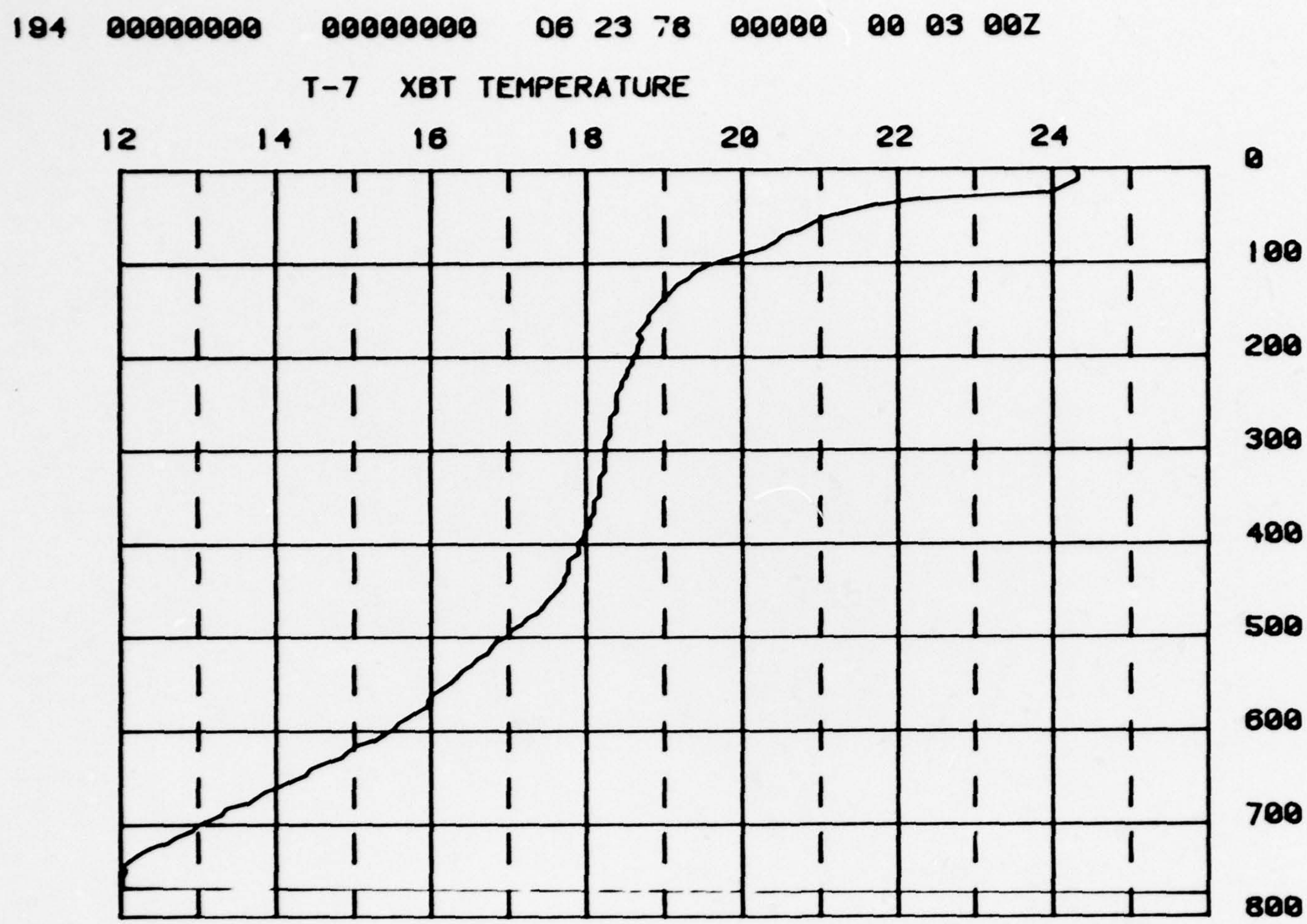

194 00000000 00000000 06 23 78 00000 00 03 00Z
T-7 XBT TEMPERATURE
12
14
16
18
20
22
24
0
100
200
300
400
500
600
700
800

FIGURE 18

selectable filters for low pass and high pass sections are shown in Figure 19.

Some Notes on Fall Rate

The fall rate, and the depth equations used in determining the depth a probe reaches after a given time, have been the subject of some debate recently. The fall rate equation for a T-7 is arrived at through averaging several drops in a deep tank and validated by intercomparison with a CTD. In regions of the ocean where substantial vertical shear is present, the probe will certainly have a horizontal component of motion and a reduction in fall rate. In addition, since the probe is rotating axially as it falls, tilts and precessional motions will produce an upward lift component due to the Magnus effect, which will also reduce fall speed. Probe-to-probe variations in weight will induce fall rate variability.

In the case of the T-11, which falls much slower than the T-7, the sideways conponent of motion of the probe will be corespondingly increased in high shear regimes.

It was not our intent, nor was it within our capability to examine these aspects of the XBT. Data represented as temperature plotted against temperature gradient, is unaffected by such variability in fall rate, and was our main way of looking

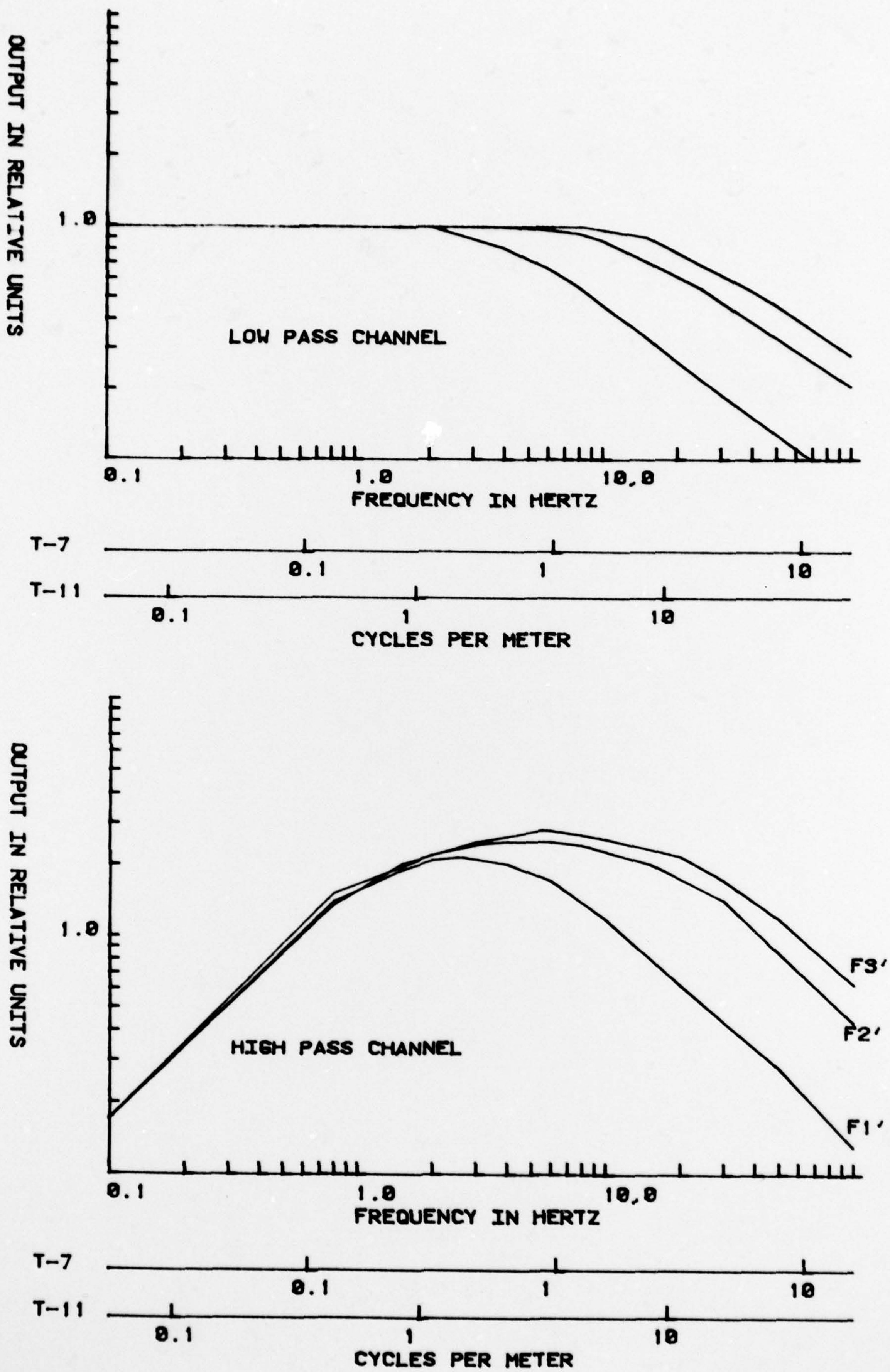

OUTPUT IN RELATIVE UNITS
1.0
LOW PASS CHANNEL
0.1
1.0
10.0
FREQUENCY IN HERTZ
T-7
0.1
1
10
T-11
0.1
1
10
CYCLES PER METER
OUTPUT IN RELATIVE UNITS
1.0
HIGH PASS CHANNEL
F3'
F2'
F1'
0.1
1.0
10.0
FREQUENCY IN HERTZ
T-7
0.1
1
10
T-11
0.1
1
10
CYCLES PER METER

FIGURE 19

at the data for scientific purposes. However, the reader should be aware of the potential difficulties in accurate depth-related profiling of the temperature field.